

## The *Swift* BAT Perspective on Non-thermal Emission in HIFLUGCS Galaxy Clusters

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### ABSTRACT

The search for diffuse non-thermal, inverse Compton (IC) emission from galaxy clusters at hard X-ray energies has been underway for many years, with most detections being either of low significance or controversial. Until recently, comprehensive surveys of hard X-ray emission from clusters were not possible; instead, individually proposed-for, long observations would be collated from the archive. With the advent of the *Swift* BAT all sky survey, any cluster's emission above 14 keV can be probed with nearly uniform sensitivity, which is comparable to that of *RXTE*, *Beppo-SAX*, and *Suzaku* with the 58-month version of the survey. In this work, we search for non-thermal excess emission above the exponentially decreasing, high energy thermal emission in the flux-limited HIFLUGCS sample. The BAT emission from many of the detected clusters is marginally extended; we are able to extract the total flux for these clusters using fiducial models for their spatial extent. To account for thermal emission at BAT energies, *XMM-Newton* EPIC spectra are extracted from coincident spatial regions so that both the thermal and non-thermal spectral components can be determined simultaneously in joint fits. We find marginally significant IC components in 6 clusters, though after closer inspection and consideration of systematic errors we are unable to claim a clear detection in any of them. The spectra of all clusters are also summed to enhance a cumulative non-thermal signal not quite detectable in individual clusters. After constructing a model based on single temperature

fits to the *XMM-Newton* data alone, we see no significant excess emission above that predicted by the thermal model determined at soft energies. This result also holds for the summed spectra of various subgroups, when systematic uncertainties are also considered, except for the subsample of clusters with diffuse radio emission. For clusters hosting a radio halo or relic, non-thermal emission is initially detected at the  $\sim 2.8\sigma$  confidence level, but the inclusion of systematic uncertainties reduces its significance. Although our samples and methodology differ, our lack of an excess at hard energies does not appear consistent with the cumulative hard excess seen in similarly summed *Beppo-SAX* PDS spectrum of cluster observations; however, some of the discrepancy dissipates after accounting for differences in the modeling of the thermal contribution at hard energies.

*Subject headings:* galaxies: clusters: general — intergalactic medium — magnetic fields — radiation mechanisms: non-thermal — X-rays: galaxies: clusters

### 1. Introduction

A number of observations, mainly at radio frequencies, have established that relativistic particles and magnetic fields are part of the intracluster medium (ICM) of galaxy clusters (e.g., Govoni & Feretti 2004). The large ( $\sim$ Mpc) scale, diffuse structures known as radio halos and relics are produced by relativistic electrons spiraling around  $\sim\mu$ G magnetic fields. Because halos and relics are not detected in every cluster, but are only found in clusters with ongoing major merger activity (Buote 2001; Schuecker et al. 2001), mergers probably temporarily reaccelerate underlying relativistic populations (e.g., Sarazin 1999; Brunetti & Blasi 2005). It is important to fully characterize the non-thermal phase if the dynamics and general state of the ICM is to be understood; the proportion of energy tied up in these relativistic components, if significant, may bias inferred mass estimates necessary to use clusters as cosmological probes (e.g., Mantz et al. 2008; Vikhlinin et al. 2009; Vanderlinde et al. 2010). Unfortunately, synchrotron emission alone cannot separately determine particle and magnetic field energy densities, and so the total energy in the non-thermal phase remains relatively unconstrained. However, the electron population can be independently observed through inverse Compton (IC) emission due to scattering of the ubiquitous Cosmic Microwave Background (CMB) photons, which are up-scattered to X-ray energies and may be observable if the electron population is sufficiently large (Rephaeli 1979). Detections of IC emission, therefore, have the potential to determine whether the non-thermal phase is energetically negligible or, particularly if the average magnetic field is large, it is sizable enough to affect the dynamics and structure of the thermal gas.

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Thermal emission clearly dominates at  $\sim$ keV energies, so searches for excess emission due to an IC spectral component are more easily undertaken at very soft or hard ( $> 10$  keV) energies. The latter range is particularly promising, given the exponential decline in the thermal spectrum and the lack of Galactic and solar wind charge exchange foregrounds that can hamper searches at soft energies (Koutroumpa et al. 2009; Takei et al. 2007; Bonamente et al. 2009). In particular, the *Swift* BAT all sky survey (Tueller et al. 2010) provides a deep map of hard energy (14–195 keV) emission from which non-thermal excesses can be identified. Its uniform coverage and impressive sensitivity makes it the most complete dataset from which to study the brightest objects in a given class (e.g., Winter et al. 2009). Whereas previous searches have concentrated on long pointed observations of individual clusters, this survey allows a larger, more uniform sample to be searched, as similarly done by Ajello et al. (2009, 2010) for detected BAT clusters. To take full advantage of this capability, we have chosen the flux-limited HIFLUGCS sample (Reiprich & Böhringer 2002), which contains the brightest clusters in the sky outside the Galactic plane. The selection of the brightest clusters may provide the greatest opportunity to detect IC emission, as in most models the nearest and most luminous clusters are expected to have the strongest IC signal. Also, because these clusters are bright and contained within a well-defined survey, there already exist good observations at lower X-ray energies, which can be used to strongly constrain the thermal properties of the ICM – an important prerequisite for the robust detection of an IC excess. Finally, the fact that HIFLUGCS is a complete flux-limited survey allows one to discuss the statistical properties of their hard excesses by stacking the individual cluster observations.

Because they are nearby and bright, many of the clusters in HIFLUGCS have been targets of IC searches with other telescopes, including A3667 (Finoguenov et al. 2010), A3112 (Bonamente et al. 2007), A3376 (Kawano et al. 2009), A2256 (Fusco-Femiano et al. 2005), A1367 (Henriksen & Mushotzky 2001), A2199 (Kempner & Sarazin 2000), and A2163 (Rephaeli et al. 2006). Most often clusters are targeted because they host a radio halo or relic, as the IC flux then leads to a direct measure of the average magnetic field strength. A large fraction of HIFLUGCS clusters were also included in an analysis of all long exposure *Beppo-SAX* observations (Nevalainen et al. 2004), which found marginal evidence for non-thermal excesses in individual clusters but a substantial excess in a stacked spectrum. In general, an IC component distinct from thermal emission in the hard band has been difficult to clearly identify, with perhaps the only counter example being an exceptionally deep observation of the Ophiuchus cluster (Eckert et al. 2008). The cluster most thoroughly searched for non-thermal emission, also in HIFLUGCS, is the Coma cluster. Controversial (Rossetti & Molendi 2004) detections with *RXTE* (Rephaeli & Gruber 2002) and *Beppo-SAX* (Fusco-Femiano et al. 2004) have recently been challenged with comparable *Suzaku* (Wik et al. 2009) observations and a detailed analysis of the *Swift* BAT survey data (Wik et al. 2011).

To perform the deepest hard X-ray survey of non-thermal emission in clusters to date, we jointly fit high quality *XMM-Newton* EPIC and *Swift* BAT spectra, extracted from identical regions and cross-calibrated to make their absolute spectral responses as consistent as possible. We describe the data and its calibration in Section 2. In Section 3, the thermal and non-thermal character of the spectra are separately analyzed, and in Section 4 they are jointly fit for each individual cluster. We also search for a statistical hard excess in sets of stacked spectra for the entire sample and for several subsamples in Section 5. Lastly, the implications of our results are discussed in Section 6. We assume a flat cosmology with  $\Omega_M = 0.23$  and  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Unless otherwise stated, all uncertainties are given at the 90% confidence level.

## 2. Observations and Data Preparation

### 2.1. *XMM-Newton* EPIC Spectra

For the lower energy BAT bands, it is very useful to have X-ray spectra at lower energies to constrain the thermal emission; this is particularly true given that the *Swift* BAT survey spectra are coarsely binned (8 channels spanning  $14 \text{ keV} < E < 195 \text{ keV}$ ). Also, any non-thermal component in the BAT spectra must be consistent with the spectra at softer energies. *XMM-Newton* is the ideal observatory to provide such complementary spectra. For one, its large field of view (FOV) allows a higher fraction of the total emission, which can be quite extended given the low redshift of the sample, to be detected in a single pointing. Additionally, the EPIC instruments are sensitive to 5–10 keV photons, which make them more useful for constraining the highest temperature gas, and the telescopes have good spatial resolution so that point sources can be excluded from the spectra. Last, but of no less importance, *XMM-Newton* has observed all but one (Abell 2244) of the clusters in HIFLUGCS. Unfortunately, another 4 cluster observations (Abell 401, Abell 478, Abell 1736, and Abell 2163) are heavily contaminated by background flares and consequently unusable (for more details, see Zhang et al. 2011). However, the data for the remaining 58 clusters are of sufficient quality to help constrain potential non-thermal signals in the BAT energy bands.

We extract *XMM-Newton* spectra for each cluster from the largest circular region that either covers the FOV or extends to the point where cosmic X-ray background (CXB) emission begins to dominate, by summing the annular spectra from Zhang et al. (2009). To ensure near Gaussian statistics for  $\chi^2$  fitting, adjacent channels are grouped until each new bin contains at least 30 counts. The centers and radii of the circular regions, along with each pointing’s observation ID, are listed in Table 1. Source spectra are extracted in con-

centric annuli within the region; corresponding particle background spectra are derived from CLOSED mode calibration data, which are renormalized based on 3-10 keV events out of the FOV and outside of a 15'.4 radius from the detector center (for details see Section 2.4 of Zhang et al. 2009). The full background treatment is described in Zhang et al. (2009). As an additional step, we readjust the normalization of the particle background spectra by hand to ensure the 7-12 keV continuum of the cluster spectra have a more physical shape. We define “more physical” as the background normalization that minimizes the  $\chi^2$  statistic for a single temperature (1T) (using the APEC plasma emission model<sup>1</sup>) individually fit to the EPIC-pn ( $2 < E < 12$  keV) and MOS1 and MOS2 ( $2 < E < 10$  keV) spectra. The new best-fit temperatures, after these initial renormalizations of the background, are compared to each other and to previous measurements (primarily Reiprich & Böhringer 2002). While this method may bias the background level, especially if a single temperature model is a poor description of a given spectrum, repeating this procedure with two temperature (2T) and single temperature plus power law (T+NT) models yield comparable or inferior results, usually favoring obvious under-subtractions of the background that produce systematic patterns in the residuals. We favor normalizations that leave the background slightly under-subtracted, in order to avoid removing a real non-thermal signature. For the most part, the overall spectrum is only mildly affected since much of the emission is at lower energies where the background is a smaller fraction of the total. One consequence is that instrumental lines, which are typically between 7.5 and 9.5 keV and mainly are a problem in the EPIC-pn spectra and which can vary in intensity relative to the background continuum, can be under- or over-subtracted. No resolved ICM lines exist in this range, so we simply ignore this region when poor line subtractions occur, as in Wik et al. (2009). Based on the change in  $\chi^2$  as the background normalization is varied, a typical 90% level uncertainty in the normalization is  $\sim 3\%$ .

We choose to model, instead of subtract, one further background component: the CXB due to extragalactic sources. Lumb et al. (2002), using *XMM-Newton* sky fields, find that this component of the CXB is well fit by a power law with photon index of 1.42 in the hard band (2-10 keV). Their results are in good agreement with other work in this band (e.g., Moretti et al. 2003; De Luca & Molendi 2004). We adopt their normalization at 1 keV of  $8.44 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \text{ sr}^{-1}$ , which is scaled to match the extraction area for each cluster. The impact of cosmic variance, or the field-to-field variation in CXB flux resulting from large scale structure and source population selection, is not included as a systematic uncertainty in the following analysis due to its small effect. While cosmic variance increases with decreasing solid angle, the high sensitivity of *XMM-Newton* allows most of the sources

responsible for a higher variance to be removed, so for one of our typical regions the 90% uncertainty is only  $\sim 10\%$  of the CXB flux. Note that Lumb et al. (2002) remove detected point sources as is done here, so their spectrum can be directly applied as is. The Galactic component of the CXB is also not considered, as it only contributes below 1 keV, and we restrict our fits to the 2-12 keV range.

## 2.2. *Swift* BAT 58-month Survey Spectra

The *Swift* mission and the properties of the survey are described in detail in Wik et al. (2011, Section 2.2) and in Tueller et al. (2010). Similarly, we refer to that Section and the appendices for details on the extraction and calibration of sources from survey image data. To briefly summarize, the flux calibration is tied to the Crab spectrum, which we define to have the same spectrum as that observed by *XMM-Newton* for  $E > 2$  keV, extrapolated to BAT energies. In this way, both the cross-normalization and spectral shape of the *XMM-Newton* and *Swift* spectra will match, and continuous models can be jointly fit to them simultaneously.

While the standard processing of coded mask imaging data is designed to extract the fluxes of point sources, it is also possible to extract the flux of a mildly extended source, albeit with somewhat greater uncertainty (Renaud et al. 2006; Wik et al. 2011). The large effective PSF (full width at half maximum FWHM  $\sim 20'$ ) for point sources in the survey means that even nearby clusters of galaxies will appear only slightly extended; the FWHM of the Coma cluster – the most extended, reliably detected source in the survey – is only 28'. From Figure 1, it is clear that detected clusters (colored circles) are typically extended, relative to other sources. The horizontal lines mark the standard deviation of best-fit FWHM values for the non-cluster sources in each signal-to-noise bin. Individual clusters are labeled in the 4 lowest energy BAT bands when they are detected at a signal-to-noise ratio greater than 5. We follow the procedure outlined in Wik et al. (2011) to extract fluxes for diffuse sources, which requires the spatial distribution of the emission to be known. Because clusters are comparable in size to the effective spatial resolution of the survey, detailed spatial models are not necessary to extract accurate fluxes. We consider generic  $\beta$ -model surface brightness profiles, which well represent the radial profiles at softer energies. Taking a representative value for  $\beta$  of 0.75, we find that all  $> 3\sigma$  detected clusters (in a given band) can be well fit with core radii  $r_c$  of either 4', 6', 8', or 10'. Profiles with  $r_c < 4'$  are hard to distinguish from point source profiles, so for any cluster emission that is too narrow to be fit with the  $r_c = 4'$  model is treated as a point source. The true spatial distribution may differ from these fiducial models, but our aim is only to extract accurate fluxes, not describe the distribution

<sup>1</sup><http://cxc.harvard.edu/atomdb/sources.apec.html>

of hard X-ray emission. For Coma, a  $\beta$ -model fit in the first BAT band (E1: 14–20 keV) yields a total flux 9% lower than that derived from a more detailed model of its spatial distribution derived from an *XMM-Newton* temperature map (see Wik et al. 2011), which accounts for the NE-SW non-axisymmetric elongation of the emission (Eckert et al. 2007). While 9% is a significant difference, Coma is one of the most significantly detected and is the most extended cluster in the survey, so this deviation, which amounts to a factor of only 1.6 times the  $1\text{-}\sigma$  error on the flux, is the largest we would expect using this set of extended models.

We also investigated the use of diffuse models for all the clusters, irrespective of their observed extent, to account for the possibility that we are missing low surface brightness emission obscured by noise. Since the spatial distribution of  $E > 10$  keV emission is unknown, we assume  $\beta$ -model profiles derived from ROSAT images (Reiprich & Böhringer 2002). For clusters with a clearly extended BAT profile, these models reasonably, but usually not perfectly, follow the emission; however, these profiles cannot be reliably distinguished from those at lower energies given that background fluctuations can still distort the profile due to the low signal-to-noise ratios. Spectral fits using these fluxes produce similar results to those we present in this work, but because their associated errors are larger, these spectra are generally less sensitive, so any additional flux captured — which is not significant — is also diluted. Therefore, these spectra are not considered further.

For clusters with modeled extended emission, we do not want to include the portion of flux that falls outside the *XMM-Newton* extraction region during joint fits of the data, since the complementary softer flux in the *XMM-Newton* band spectra is not present. Therefore, only the fraction of the flux that resides within the *XMM-Newton* region is included in the spectra derived here. One uncertainty, particularly when emission is detected at lower significance, is where the emission is actually coming from, given the positional accuracy of the survey (a  $5\sigma$  source detected in a given band has a 90% error circle of radius  $6'$ ). Since the E1 band-derived positions are near the center of the extraction region, within their respective error circles, we assume the center of the hard band distribution is coincident with the center of the *XMM-Newton* extraction region except for A754, A3266, and A2256. For these detected clusters, their BAT positions are somewhat offset from the surface brightness peak due to an anisotropic temperature distribution produced by mergers (see, e.g., Henry & Briel 1995; Finoguenov et al. 2006; Sun et al. 2002). Following this procedure, we will not underestimate the coincident flux, although overestimates may result that could lead to incorrect hard excesses. However, since we are unable to significantly detect non-thermal emission individually in any of the clusters, this procedure can only cause us to be biased in favor of more conservative upper limits.

### 3. Separate Fits to Individual *XMM-Newton* EPIC and *Swift* BAT Spectra

Before combining the *Swift* and *XMM-Newton* datasets, we characterize each telescope’s spectra separately. The goal is to identify any problems with the data or our methodology that might lead to biased results when the spectra are fit jointly.

#### 3.1. Single Temperature Fits to the EPIC Spectra

The motivation for including *XMM-Newton* spectra in the analysis is to fully characterize the thermal properties of the hottest gas in the ICM, which will contribute flux to the BAT energy bands. Similarly, these lower energy spectra must be consistent with any indication of a non-thermal component in the BAT spectra; for example, a steep power law may best describe the BAT data but at lower energies result in a poor description of the spectrum. Since our purpose is not to fully characterize the total emission detectable by *XMM-Newton*, but only capture the state of the hottest gas, we ignore all events with energies below 2 keV. Cool ( $\lesssim 1$  keV) gas is completely unimportant at BAT energies, and it will not overly bias  $E > 2$  keV data. We therefore initially consider EPIC spectra in the 2–12 keV range for the pn and 2–10 keV range for the MOS detectors; including photons down to 2 keV provides additional leverage during spectral fitting, since most of the detected photons, regardless of temperature, are at lower energies.

However, the lower end of this energy range presents two issues. First, bright  $\sim 1$  keV gas can significantly contribute to the emission between 2 and 3 keV, which certainly exists in some of the cool core clusters in HIFLUGCS. In single temperature fits, the average temperature will then be biased low to accommodate this component, which could lead to thermal emission being interpreted as a non-thermal excess. Multi-temperature fits would alleviate this problem, but most of the *XMM-Newton* data are not of sufficient quality to strongly constrain more than one temperature component in this energy range. Including  $E < 2$  keV data to better constrain multi-temperature fits would also require a more complicated analysis that will involve more free parameters and, because the highest signal-to-noise ratios are in the  $\sim 1$  keV channels, fits would be driven by this data, possibly resulting in biased high temperature components. The second issue relates to the imperfectly calibrated gold edge at 2.2 keV, where the response drops somewhat abruptly. While on its own this feature does not strongly impact spectral fits, because it lies near the edge of our energy range where the signal-to-noise ratio is largest, secondary model components can be “co-opted” into better fitting this edge. For instance, in a spectrum truly described by a gas at a single temperature, the addition of a second temperature or non-thermal component to the fit will cause the second component to “fix” any deviations at this edge, typically resulting

in a low temperature or steep photon index that has no real physical counterpart.

In practice, both of these effects can conspire to produce the appearance of a more significant non-thermal spectral component than is warranted by the rest of the data. To counter both issues, we also perform fits to data with energies  $E > 3$  keV, which exclude the gold edge and any sizable emission from  $\lesssim 1$  keV gas. These spectra have lower signal-to-noise due to excluding the 2–3 keV emission, but the high fluxes of clusters in our sample reduce this issue's importance. Single temperature fits in both the 2–12 keV and 3–12 keV ranges, jointly fit to all three EPIC spectra (except for A3526, for which the MOS-1 spectrum is ignored, and for A2142 and A2147, for which the MOS-2 spectra are ignored), are given in Table 2. The pn and MOS instrument cross-normalization is left as a free parameter, which allows for a typical  $(10 \pm 10)\%$  difference between their calibration (e.g., Snowden 2002). This cross-normalization factor is used and kept fixed during all subsequent joint EPIC-BAT fits. The change in the best-fit temperature from the  $E > 2$  keV to  $E > 3$  keV fits is only  $\sim 0.3$  keV on average, indicating that the temperature is generally robust to the choice of the energy range, but that higher energy photons come preferentially from higher temperature gas, assuming the true temperature structure is not isothermal but contains a continuous spectrum with gas at many temperatures due to substructure and/or radial gradients (Cavagnolo et al. 2008; Snowden et al. 2008).

### 3.2. Non-thermal Fits to the BAT Spectra

Our goal is to detect a non-thermal spectral component at hard energies, but because the statistical weight of the BAT channels is so much less than the EPIC channels (lower S/N and fewer of them, at least by an order of magnitude), we have to be careful not to let the *XMM-Newton* data unfairly drive the spectral fits. To assess the sensitivity of our BAT spectra, we extract 10,000 blank sky spectra from uniformly distributed, random positions at least  $40'$  from any known sources and greater than  $20^\circ$  from the Galactic plane, to mimic the selection function in HIFLUGCS. We then fit these spectra with a fiducial power law model of photon index  $\Gamma$  fixed at a value of 2, roughly the expected slope for IC emission inferred from radio halos and relics. The distribution of best-fit normalizations from these power law fits are presented in the narrow histogram in Figure 2. They are well fit by a symmetric Gaussian (dashed smooth line) and indicate a  $1\sigma$  sensitivity threshold of  $\sim 2 \times 10^{-12}$  erg  $\text{cm}^{-2} \text{s}^{-1}$  (20–80 keV). Similarly, the formal  $3\sigma$  detection level is  $5.8 \times 10^{-12}$  erg  $\text{cm}^{-2} \text{s}^{-1}$ . In principle, the BAT survey is sensitive enough to confirm or reject previous detections of hard excesses with fluxes  $\sim 10^{-11}$  erg  $\text{cm}^{-2} \text{s}^{-1}$  (e.g., Rephaeli & Gruber 2002; Molendi et al. 2002; Fusco-Femiano et al. 2004).

Now we wish to compare our cluster spectra with this distribution, but first we have to account for any thermal emission in the lower energy bands. The single temperature models derived with *XMM-Newton* (2–12 keV) are included as a second component along with the power law model, with only its normalization left as a free parameter. The resulting non-thermal normalizations are also given in Figure 2 as both the wider histogram (scaled up) and as the vertical lines (showing individual values). While the majority of cluster non-thermal components are consistent with the blank sky fits, there is a tail at positive normalizations possibly indicative of a non-thermal excess. However, the thermal contribution is not well determined in this method and may be underestimated. Intriguingly, the three clusters with the most significant non-thermal component (A2029, A1367, and A1651) have positive fluxes, although marginally detected, in all 8 BAT bands; this rarely occurs for the blank sky spectra. We discuss these clusters in more detail later. The main result from this analysis is that the BAT cluster spectra have probably not reached a sensitivity level sufficient to detect hard, non-thermal excesses, if they exist, in the brightest clusters.

## 4. Joint Fits to the EPIC-BAT Spectra

BAT fluxes are calibrated to match both the normalization and the spectral shape of sources as detected by the *XMM-Newton* EPIC-pn instrument (Wik et al. 2011), and they are extracted from regions identical to the *XMM-Newton* extraction regions. As such, continuous spectral models can be used over the full 2–195 keV energy range to simultaneously fit both the *XMM-Newton* and *Swift* spectra. However, in individual cases the cross-normalization factor,  $f_{CN}$ , may stray from a value of 1 as it does between the pn and MOS instruments (see Section 3.1). We therefore adopt, along with a 3% uncertainty in the *XMM-Newton* background normalizations, a conservative 10% systematic uncertainty for  $f_{CN}$ . Because no compelling evidence for non-thermal emission is found in the nominally calibrated spectra (see analysis below), we only consider these uncertainties when deriving 90% confidence interval upper limits.

### 4.1. General Properties from the Joint Analysis

For each cluster, 3 simple spectral models are employed to describe the emission covering 2 orders of magnitude in energy: a single temperature thermal model (1T), a two temperature model (2T), and a thermal plus non-thermal model (T+IC). Due to the limited sensitivity of the *Swift* data, more complicated models cannot be constrained; for example, the separate temperature components in the 2T model are generally poorly constrained in our analysis.

Above 50 keV, the APEC emission model is replaced with MeKa because APEC is not defined above 50 keV in the implementation of XSpec used here (Version 12.6.0k). Note that the MeKaL emission model could also be used continuously across this energy range, if the look-up table switch is turned off. For the thermal component, the temperature, abundance, redshift, and normalization are all varied. The individual abundances and redshifts in the 2T model are tied together. The non-thermal photon index is initially fixed at  $\Gamma = 2$ , typical of radio halos, and the normalization is allowed to vary; when the photon index is fit for, it is always fixed to the best-fit value before errors for other parameters are derived. In general, the photon index is poorly constrained, allowing for a wide range of normalizations, which are then less straightforward to evaluate. The purpose of fitting for the photon index is to make sure that we are not biased against detectable IC components with indices that differ from the fiducial value.

Because of complications arising at energies between 2 and 3 keV (see Section 3.1), we perform these fits for both the 2–195 keV (Table 3) and the 3–195 keV (Table 4) spectral ranges. The  $E > 2$  keV fits, at first glance, suggest that there may be evidence for a non-thermal component in a majority of HIFLUGCS clusters. Many of the clusters with some evidence, at least at the 90% level, of a non-thermal excess are, unexpectedly, low temperature clusters without significant detections at BAT energies. In these cases, the non-thermal component is serving to “adjust” a problem at lower energies – due to either incompletely modeled low temperature components, an imperfectly calibrated response at the gold edge, or both. The significance of these instances will disappear from fits within a slightly higher energy range, while real non-thermal emission will become a higher proportion of the total flux and so this component should not greatly diminish in significance. A drastic reduction in the number of marginally detected non-thermal excesses is seen when comparing Tables 3 and 4; only 6 clusters are detected to have such emission at the 90% confidence level (statistical). These clusters will be discussed individually in Section 4.2.

While the 3–12 keV band avoids some possible systematic uncertainties with the *XMM-Newton* response and complications from cooler gas, the narrower range may reduce our ability to strongly constrain multi-temperature components in the spectra. One concern is that a weak non-thermal emission component might be indistinguishable from a purely thermal model with a slightly elevated temperature. Note, however, that the 3–12 keV band temperatures in Section 3.1 are typically only  $\sim 0.3$  keV higher than the 2–12 keV temperatures. Therefore, the 1T model temperatures should agree for the joint fits over both energy ranges, which is found to be the case in Figure 3. Temperatures derived from joint fits are consistent with those found using only the *XMM-Newton* spectra, for both energy ranges. For the most part, temperatures from the joint fit 3–195 keV fits are in good agreement with or slightly lower than the 3–12 keV temperatures. The contribution

of the BAT data in this case is to somewhat *lower* the best-fit temperature, contrary to the expectation if a detectable non-thermal excess were present. The 3–195 keV non-thermal flux limits and possible detections (90%, statistical) are shown in Figure 4.

## 4.2. Individual Cases

Six clusters have a formal detection of non-thermal emission in the 3–195 keV band. Two of these 6 clusters are also in the top 3 of candidates for emission based on their BAT-only fits: A1651 and A2142. The other cluster in this top 3 – with the largest non-thermal normalization of all the clusters – is A2029, so we will include this cluster with the 6 “detected” clusters as worth some brief discussion. The clusters are listed in order of decreasing non-thermal flux.

*A2029* (Fig. 5): This hot ( $\sim 8$  keV), cool core cluster has been studied in detail with *Chandra* (Clarke et al. 2004), who explore the interaction between cool gas and the radio AGN in the cluster center. The cluster is elongated but relatively regular; no evidence exists for major merger activity; however, a minor merger may be producing the spiral surface brightness enhancement in the center. Also, no evidence for an X-ray counterpart of the AGN is visible in the *Chandra* data. In addition to the radio jets, the core of the cluster is also host to an extended radio minihalo (Murgia et al. 2009). As with radio halos and relics, IC emission may be detectable from the minihalo if the magnetic field is small; Taylor et al. (1994) measured a lower limit of  $B \gtrsim 0.11\text{--}0.19 \mu\text{G}$  with Faraday RM observations of the jet. The implied magnetic field strength, if we take as the IC flux that found with the 2–195 keV fit, is  $B \sim 0.08 \mu\text{G}$ , roughly consistent with their field strength.

But have we really detected IC from the cluster core? The significance of the non-thermal component completely disappears in the 3–195 keV fit; all three model combinations match the data equally well. Also, the 2T model formally provides a better fit to the 2–195 keV spectrum where the non-thermal component is detected. The second temperature component,  $\sim 0.3$  keV, is consistent with a low temperature component of 0.11 keV observed by Clarke et al. (2004). Given these results, it is more likely that the non-thermal component is trying to mimic the low  $kT$  cool core component in the 2–3 keV range, since its significance disappears if this energy range is ignored. However, it is worth noting that the BAT data do generally support hard emission at higher energies, although at low signal-to-noise. Such hard emission could be due, on the other hand, to heavily obscured AGN emission from the central source at a level not quite detectable in the 58-month survey. The spatial distribution of BAT emission is consistent with that from a point source in all bands.

*A1651* (Fig. 6): This cluster has a weak cool core, which means that while there is no significant temperature gradient in the center, the cooling time of the gas in the center is short (Hudson et al. 2010). Given the similarity between its BAT data and that of A2029, an obscured AGN of similar flux could be responsible for the marginally detected positive flux in the higher energy bands. However, in this case the T+IC model is a significantly better fit than is the 2T model;  $\Delta\chi^2$  improves by 9 (2–195 keV) and 5 (3–195 keV) over the 1T and 2T models. If there were no hard excess, the probability that the 6 highest energy bands measure flux above the thermal component, given that BAT fluctuations are Gaussian, is  $(\frac{1}{2})^6$ , or 1.6%, which is not impressive in a sample of 58 clusters. The BAT spectrum is certainly suggestive, but considering the excess is not significant at the  $3\sigma$  level for the 3–195 keV fit, and only just at this level in the 2–195 keV fit – without including systematic uncertainties – we cannot claim to have detected a non-thermal component in this cluster. However, the evidence is perhaps strongest in this case, which is contrary to the expectation that such an excess is most likely in a merging cluster, particularly one with a radio halo or relic.

*A2142* (Fig. 7): As the hottest cluster in the sample, the BAT is easily able to detect this cluster’s high energy emission, which we might expect to exhibit a non-thermal excess since it also hosts a radio halo (Giovannini & Feretti 2000). Both the T+IC and 2T models indicate that hard excess emission may be present; in the latter case, the second temperature component is unphysically high, acquiring the highest allowed temperature value. However, Nevalainen et al. (2004) estimate that 2 Seyfert galaxy nuclei within  $17'$  of the cluster center contribute  $\sim 30\%$  of the hard band emission detected by *Beppo-SAX*; a similar amount of contamination would be expected in the BAT spectrum. Unfortunately, the *XMM-Newton* observation places this cluster right on the edge of the FOV, so over half (55.6%, based on a comparison with a pointed *ROSAT* PSPC image) of the soft band emission is missing from the EPIC spectra. We rescale the *XMM-Newton* spectra to correct for the lost flux; the BAT source is equivalent to a point source, so it is not possible to correct the BAT emission for the *XMM-Newton* FOV. The correction to the *XMM-Newton* flux could be off by a sizable factor if the  $E > 2$  keV emission is distributed differently than the  $E < 2$  keV emission where *ROSAT* is sensitive. The significance of the non-thermal excess here is only at the  $2\sigma$  level, mainly due to the poor statistics at *XMM-Newton* energies. While inconclusive, the BAT spectrum warrants further analysis using better data below 12 keV.

*A3112* (Fig. 8): Using both *Chandra* and *XMM-Newton* data, Bonamente et al. (2007) have claimed to see both a hard and soft excess that is consistent with a non-thermal origin. If this is the correct interpretation of these spectra, the IC excess would be clearly detectable in the BAT spectrum given our sensitivity. While a non-thermal component is detected in our joint fits, it has well below the predicted flux of Bonamente et al. (2007); our  $3\sigma$  upper

limit on the non-thermal normalization, using a photon index  $\Gamma = 1.8$  that matches their best-fit value, is 3 times lower than their estimate. The quality of our 1T model fits is significantly less than for either the 2T or T+IC models; while those fits are of similar quality, the 2T fit yields physically reasonable temperatures and lower  $\chi^2$  values ( $\Delta\chi^2 \sim 3$ ) than the T+IC model over both energy ranges. A non-thermal excess may in fact exist in this cluster, but a perhaps more likely scenario is that the ICM here is less isothermal than is typical in clusters, requiring several temperature components to adequately explain the cluster emission. In any case, the BAT data do not argue strongly in favor of an IC interpretation for the excess emission above  $\sim 7$  keV observed in the *XMM-Newton* data; as can be seen in Figure 8, the power law component nearly ubiquitously overpredicts fluxes in the BAT spectrum. A more detailed exploration of the spatial and thermal structure at  $E < 12$  keV is certainly warranted.

*A1367* (Fig. 9): This cluster hosts a radio relic in its outskirts (Gavazzi & Trinchieri 1983), and so IC emission is expected at some level in the radio relic region; however, the *XMM-Newton/Swift* extraction region does not contain the relic, so we are unable to address the magnetic field strength. Using *RXTE*, Henriksen & Mushotzky (2001) potentially detect a non-thermal component, although a two temperature fit better describes their spectrum. The marginally detected IC emission we see is consistent with their non-thermal flux, whether we use a photon index of 2.0 or their value (based on the spectrum of the radio relic) of 2.9. Our 2T model fit, in the 2–195 keV band, is as good as the T+IC model fit, and given the marginally detected fluxes in the BAT bands, a 2T description of the ICM in this early stage, forming cluster cannot be ruled out.

*A2589 & Fornax*: Neither of the BAT spectra of these clusters show particular evidence that they have detected emission of any kind in any band. The first 2 bands of A2589’s spectrum are just inconsistent with zero flux at the  $1\sigma$  level, but a marginal detection in these bands is consistent with the thermal component. In both cases, the BAT spectrum is not sensitive enough to exclude the non-thermal component driven by the *XMM-Newton* data; since the BAT data do not further constrain the non-thermal component in these cases, we will not discuss these clusters further.

### 4.3. Upper Limits

While some evidence for non-thermal emission is present in several of the HIFLUGCS clusters, in none of these cases is a significant excess indicated by both the BAT and EPIC spectra that could not plausibly be explained by a multi-temperature state of the ICM. In many cases, the BAT spectra simply lacked the signal-to-noise to meaningfully constrain the

existence of excess emission; we therefore derive upper limits for a non-thermal component in our joint spectra. Three limits are presented for each energy range (2–195 keV and 3–195 keV) considered: a 90% confidence level limit including systematic uncertainties in  $f_{\text{CN}}$  and the EPIC backgrounds, as described in Section 2.1, and two  $3\sigma$  limits, without systematic uncertainties included, for our fiducial photon index of  $\Gamma = 2$  and for the best-fit value of  $\Gamma$ . After fitting for  $\Gamma$ , it is then fixed at that value when the upper limit is computed. The systematic terms are included in the 90% limits as described in Wik et al. (2009). Upper limits are reported as 20–80 keV fluxes in units of  $10^{-12}$  erg cm $^{-2}$  s $^{-1}$  in Table 5. In some instances, usually for lower temperature clusters, the 90% limit exceeds the  $3\sigma$  limits; in these fits, the systematic uncertainties in  $f_{\text{CN}}$  and/or the EPIC background dominates over the statistical uncertainty in the spectra. For example, in a low temperature cluster lowering the EPIC backgrounds significantly hardens the spectra, while modifying  $f_{\text{CN}}$  such that already poorly constraining BAT fluxes are 10% higher, will allow a much larger IC-like component to fit the data than would be allowed statistically. In hotter clusters, adjusting the background has less of an effect on their spectral shape, and because they are hot they tend to be more significantly detected by the BAT, so that modifying  $f_{\text{CN}}$  cannot drastically affect the non-thermal component.

## 5. Joint Fits to Stacked EPIC-BAT Spectra

In some clusters, as noted above, hints of a non-thermal excess are present, even if we cannot argue for their definite detection. If the excess does exist in several clusters, but just below the detection threshold, we may be able to increase the signal-to-noise enough for a statistical detection by stacking the cluster spectra. For simplicity, we stack only the EPIC-pn *XMM-Newton* spectra, which have the highest sensitivity especially at higher energies. Stacking the MOS spectra would be complicated by the variable pn/MOS cross-calibration factor and the fact that 3 of the cluster MOS spectra have been excluded from our analysis. Both the pn and BAT spectra are straightforwardly summed, as are the pn backgrounds, and their errors are propagated. Because the same response matrix is used for all the BAT spectra, we are able to use this unmodified file with the stacked spectrum. To create an average response matrix for use with the stacked pn spectrum, we first multiply the individual redistribution matrices by their respective auxiliary response files, which contain the effective area per incoming photon energy. Then, a weighted average is performed on the new response files, with weighting factors proportional to each spectrum’s 2–7 keV count rate. This procedure ensures that the final response matrix will best represent the instrumental response for the majority of photons. In any case, an unweighted response file was also created and no significantly different results were produced when using it. The CXB model

normalizations were summed and included in the spectral fits.

In all, we create 8 stacked spectra based on different groupings of the 58 HIFLUGCS clusters for which we have *XMM-Newton* data: “All” clusters, “Hot” ( $kT > 7$  keV, from the 2–12 keV fits), “Cool” ( $kT < 7$  keV), “Radio” clusters hosting a radio halo or relic, “No Radio” clusters that do not host a known halo or relic, non-cool-core clusters (“NCC”), strong cool core clusters (“SCC”), and weak cool core clusters (“WCC”), as defined by Hudson et al. (2010) and listed in Table 1. These categories are designed to separate the sample into subgroups which might have different average levels of non-thermal emission. For example, IC emission must exist at some level in clusters with a radio halo or relic, but may not be present in clusters more generally. Thus, we might expect the “Radio” clusters to preferentially have non-thermal excesses, which are enhanced when they are stacked together and not diluted by the additional spectra from “No Radio” clusters that have no such excess.

Because these clusters span a large range of temperatures and redshifts, it is not appropriate to model the summed spectra with a single or even several temperature model for the thermal component. Instead, we build multi-temperature models from the previous spectral fits, for which we keep the spectral shape fixed and only allow the overall normalization to vary during fits to the stacked spectra. We consider the *XMM-Newton*-only single temperature fits (Table 2) derived from 2–12 keV (1T $_{X,>2}$ ) and from 3–12 keV (1T $_{X,>3}$ ), and the single (1T $_{\text{J}}$ ) and double (2T $_{\text{J}}$ ) temperature fits derived from the 2–195 keV joint spectra (Table 3). To search for non-thermal emission in the stacked spectra, a power law model is added to represent the IC component and the normalization of the thermal model is allowed to vary. Ideally, the shape of the thermal component would be able to adjust to accommodate the IC signal, as it effectively does in the individual joint fits via the temperature parameter. However, the non-thermal flux below 12 keV will be small and should not cause the temperature to change in any significant way. For the 2T $_{\text{J}}$  model, we want to avoid including unphysical temperature components that may have been driven by calibration features at the edges of the spectral range in the individual 2T fits. A low temperature ( $\lesssim 2$  keV) component’s emission measure may cause  $< 2$  keV emission to be significantly overestimated in order to better fit the gold edge, for example. Similarly, a slight under-subtraction of the *XMM-Newton* background or positive fluxes in the higher energy BAT bands may lead to unrealistically high temperatures. In Figure 10, we plot the temperature values for this model relative to the 1T $_{\text{J}}$  model temperatures. We have removed unphysical temperature components from both the 2T $_{\text{J}}$  model; the best-fit single temperature model is used in place of the 2T model for those clusters, which are represented by blue circles in Figure 10. Unphysical temperature components were found to have  $kT > 16$  keV and  $kT < 2.1$  keV, if their 1T $_{\text{J}}$  temperature is greater than 3.5 keV. In general, this latter cut eliminates temperature components that significantly over-predict the  $0.5 \text{ keV} < E < 2 \text{ keV}$



emission.

Thermal and thermal plus non-thermal fits to the stacked spectra are given in Table 6. Considering only the fits to data with  $E > 3$  keV, which excludes the most problematic region of the spectra, we find *no* evidence at the statistical 90% level for a non-thermal component in any of the stacked spectra. In the table, the normalization of the thermal component in the “ $T_{\text{Model}}$ -only” fits is not shown, only its  $\chi^2$  value for comparison purposes. For the “ $T_{\text{Model}}+\text{IC}$ ” fits, the photon index is fixed to  $\Gamma = 2$  as was done previously for the joint fits. The last 3 columns report the “ $T_{\text{Model}}+\text{IC}$ ” fits with  $\Gamma$  as a free parameter; however, its value is fixed when errors are computed. In this case, the photon index was initialized as  $\Gamma = 1$ , so for spectra with no particularly strong indication of non-thermal emission, the best-fit normalization was set to zero and the photon index kept at or near its initialized value; this explains why so many of the “best-fit” photon indices presented in the table are near unity. In the case of large values of  $\Gamma > 3$ , the non-thermal component is attempting to either represent incompletely modeled soft emission from low temperature gas or correct an imperfectly calibrated gold edge. Even though these normalizations are large and quite significant, they are so steep that the flux at hard energies is negligible and does not represent an IC excess. If  $< 2$  keV emission were included in the fits, these large  $\Gamma$  values would disappear as they would vastly over-predict the soft emission.

In Figure 11, the jointly fit stacked spectra for all 58 clusters is shown with the  $1T_{X,>2}$  model. The best-fit model normalization agrees with its expected value to better than 1%, as do all the model fits without an IC component, indicating that the average pn response is accurate. Also, a difference in spectral shape appears below 3 keV, visible in the residuals, that highlights the problem with including this emission in the fits. The BAT data are well represented by this model, *even though the temperature models were derived from fits to the XMM-Newton spectra alone*. The regular pattern in the BAT residuals is likely real, and is apparent in most of the spectra of hot clusters such as Coma (see Wik et al. 2011). When considering only one cluster, it seemed reasonable that this residual pattern could simply be due to chance. The pattern reappears in many of the individual joint fits however, indicative of a systematic problem. Because the BAT flux calibration is dominated by normalizing to the Crab flux in each band, these fluxes are really only accurate for objects with a spectral slope similar to the Crab’s. At these energies, cluster spectra are quite steep even for the hottest temperatures, so some miscalibration would be expected. Most likely, the first and possibly second energy bands have underestimated fluxes, owing to the rapid rise of the instrumental response with energy; clusters have proportionately more emission at the lower energy part of the band than does the Crab, and so the internal band response is miscalibrated – weighting the higher energy part of the response more strongly than is appropriate for thermal emission. While this certainly affects our results, the only solution

is develop a detailed response matrix model for the survey data. Unfortunately, the detailed spectral response for the *Swift* survey data currently has much larger uncertainties than the Crab spectrum itself.

In general, the addition of a non-thermal component to these spectra does not significantly improve the fits in Table 6, *except* for the “Radio” subsample. The “All,” “Cool,” “No Radio,” and “WCC” stacks are found to lack a physically plausible ( $\Gamma \lesssim 3$ ) non-thermal component at the statistical-only 90% level. For the “Hot” and “NCC” sample fits, the IC component significance for the  $\Gamma = 2$  case is not repeated when  $\Gamma$  is left as a free parameter. In contrast, the “Radio” and “SCC” cluster samples both have somewhat significant non-thermal components with  $\Gamma \sim 2$  that improve the fits relative to the single temperature case when either the  $1T_{X,>2}$  or  $1T_J$  models are used to describe the thermal emission. At first glance, both of these subsamples appear to have evidence for a true IC-like component in their spectra; however, when the quality of the various fits is considered, only the Radio subsample achieves its lowest  $\chi^2$  value with the  $T+\text{IC}$  models. The SCC stacked clusters, on the other hand, are better described by the two-temperature model, which is not surprising given the flux contribution at  $E \sim 2$  keV energies of high emissivity gas in their cool cores. Most likely, the power law component in this case is attempting to mimic part of this emission not perfectly-fit by the inappropriate single-temperature model fit.

The best-fit non-thermal plus  $T_{X,>2}$  model for the Radio clusters is shown in Figure 12. For comparison, the  $T_{X,>2}$  and  $2T_J$  fits with no IC component are shown in Figure 13 and Figure 14, respectively. The non-thermal component, plotted as a dotted line in the figure, becomes competitive with the thermal emission in the 35–50 keV band, where a somewhat significant excess is present in thermal-only model fits. By contrast, the “No Radio” subsample shows no evidence for an excess at hard energies (Fig. 15).

Ignoring systematic uncertainties, the non-thermal signature is detected for the Radio clusters with  $2.8\sigma$  confidence using the  $T_{X,>2}$  model and  $1.6\sigma$  with the  $T_{X,>3}$  model. Including an  $f_{\text{CN}}$  uncertainty of 3.33% – the nominal 10% uncertainty is unlikely to occur in the same direction in all clusters, so it is approximately reduced by the square root of the number of stacked clusters – reduces the significances to  $2.3\sigma$  and  $1\sigma$ , respectively. While only a very marginal detection, especially considering the  $T_{X,>3}$  model fit, which should be less biased, it is encouraging that the subsample that would be expected to contain a non-thermal component shows the most significant evidence for such an excess above the thermal continuum.

## 6. Implications and Discussion

In this work, we characterized the hard X-ray emission from HIFLUGCS, a sample of the brightest galaxy clusters outside the Galactic plane. For the 58 out of 63 clusters with usable *XMM-Newton* data, we searched for excesses over the thermal emission from gas in the ICM in data from the 58-month *Swift* BAT all-sky survey. EPIC and BAT spectra were extracted from identical regions and carefully calibrated to allow straightforward joint fits that simultaneously constrain the thermal and non-thermal emission in both spectra. We first considered fitting over an energy range of 2–195 keV but found that low temperature gas and the gold edge in the *XMM-Newton* spectra could lead to false detections. Ignoring the 2–3 keV data resolved this issue, although a somewhat weaker constraint on the thermal component reduced our overall sensitivity. From the 3–195 keV fits, six clusters were found to have marginal evidence for a non-thermal excess, although none of these were deemed significant enough to claim a detection, especially considering systematic uncertainties in the EPIC background and EPIC-BAT cross calibration normalizations. We then stacked the spectra to look for a significant statistical detection of non-thermal emission in the HIFLUGCS sample. Unfortunately, the stacked spectra revealed no definitive excess. Stacking subsamples of the HIFLUGCS clusters returned similar results, except for a tantalizing but very marginal detection of a non-thermal component in the stacked spectrum of all clusters that host radio halos and/or relics — the very clusters that are most expected to have detectable IC emission.

The lack of definitive hard X-ray excesses in our individual clusters is consistent with the most recent searches with *Suzaku*, *INTEGRAL*, and *Swift*, though somewhat less so with those of *RXTE* and *Beppo-SAX*. Ignoring the Coma cluster, whose controversial hard energy emission is discussed at length elsewhere (e.g., Wik et al. 2011), our analysis is not clearly inconsistent with any previous observations, particularly given that the possible existence of low-level, extended non-thermal emission has not been considered in detail here (as in Wik et al. 2011), which *RXTE* and *Beppo-SAX* in particular would be sensitive to given their large FOVs. For the clusters in our sample also observed by *RXTE*, A3667 (Rephaeli & Gruber 2004) and A2256 (Rephaeli & Gruber 2003), our upper limits agree with analyses of their data, at least considering the two-temperature interpretation allowed for A2256, regardless of the distribution of emission. The recent *RXTE* detection of non-thermal emission in NGC 5044 below 15 keV by Henriksen (2011) lies below our detection threshold at higher energies. For several of the clusters observed with *Beppo-SAX* and found to host non-thermal emission, such as A2256 (Fusco-Femiano et al. 2005), A2199 (Kaastra et al. 1999), and A3526 (Molendi et al. 2002), our upper limits fall below their measured inverse Compton fluxes. Kaastra et al. (1999) claim an extended non-thermal halo for A2199 between 0.5 and 1.5 Mpc, which is not inconsistent with its larger size at high energies (14–20 keV, see Fig. 1); however, due to

the low S/N of the detection, this extent is also indistinguishable from that of a point source. Upper limits from *Suzaku* for clusters A3667 (Nakazawa et al. 2009) and A3376 (Kawano et al. 2009) are obviously consistent with these results.

Similar studies of clusters detected by the BAT (Ajello et al. 2009, 2010) have also failed to find definitive non-thermal excesses. The only discrepancy is for A3667, for which both Ajello et al. (2010) and Nakazawa et al. (2009) detect high temperature ( $kT \sim 15$ ) keV gas near the center. While we do not see strong evidence for a significant high temperature component like this – although our 2T, 2–195 keV fit does suggest a significant amount of hot gas ( $kT \sim 9$  keV) – the elongated shape caused by its ongoing merger requires a more detailed analysis to more accurately extract its BAT fluxes to properly assess this high temperature component. In any case, a noteworthy difference between the methodology here and in Wik et al. (2011) with that of Ajello et al. (2009, 2010) is our use of the technique developed by Renaud et al. (2006) to recover extended source fluxes from coded mask observations. This procedure allows for a more direct spatial comparison between soft and hard X-ray spectra such that no assumptions about the extent of hard band data need to be made; however, the low relative extent and signal-to-noise generally achieved makes this advantage critical only for the largest, brightest clusters such as Perseus and Coma.

While some excesses in the stacked spectra are tantalizing, equally good, and sometimes better, fits result when the 2T<sub>J</sub> model is used. Since only the normalization is allowed to vary in these fits, it is hard to justify why the addition of an IC component really provides a better description of the data, especially if the improvement in  $\chi^2$  is minor. Note that this comparison is only fair because the 2T models are all physically reasonable descriptions of the ICM, otherwise we may be inappropriately modeling non-thermal emission with an incorrect thermal component. The upper limits on non-thermal emission in the stacked spectra, when applied on average to the clusters making up the stacked sample, are more constraining than limits from individual fits. The typical 90% confidence level upper limit on the cumulative IC flux in the stacked spectra is  $\sim 2 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> in the 20–80 keV band, which translates to an average flux per cluster 9 to 58 times lower than this limit. However, since it was not possible to allow the combined thermal components in the composite models to adjust slightly when fitting with the power law component, this limit is overly strict.

These results are in conflict with an analysis of a similar sample of clusters observed by *Beppo-SAX* (Nevalainen et al. 2004), which found systematic if marginal excesses for merging clusters. Actually, these previous IC flux estimates are not unlike our results in the 2–195 keV range, as are the temperatures of the thermal component for clusters in both our and their samples. However, over the 3–195 keV energy range, the 90% error interval for nearly all the excesses include zero. This result is at least partly due to slightly higher

best-fit temperatures (see Section 3.1 for a more detailed discussion). Since clusters are not isothermal, harder spectra such as those from the BAT will contain proportionately more photons from higher temperature gas. An example of this bias can be seen in the stacked spectrum of Nevalainen et al. (2004); they observe a highly significant non-thermal excess, but the steep IC component necessary to explain it would lead to detectable amounts of non-thermal emission at softer energies, which is not seen. The authors interpret this as evidence that the non-thermal emission is significantly extended. Our BAT data test this possibility, as extended emission is both detectable and not detected by the BAT beyond that produced by the thermal gas. Thus, it is unlikely that the non-thermal emission is very highly extended and strong. In fact, the steep excess in their spectrum is exactly what would be expected for a strongly multi-temperature thermal structure – which naturally results when many clusters spanning a broad range in temperature are summed – that is modeled as a single temperature component, which is what they do. When we model our stacked BAT spectrum this way, we find a temperature consistent with the average temperature of our clusters and a very significant, steep ( $\Gamma \sim 2.8$ ) power law component, identical to their best-fit photon index. But the thermal component, *determined at hard energies*, will be more highly weighted by hotter clusters, whose emission dominates. If a single temperature component is used to model the thermal emission for such a summed spectrum, then at the very least the temperature needs to be fixed to the weighted-average value in the band in which the hard excess emission is expected to be found. For example, in our sample, the count rate weighted-average temperature jumps from 5.6 keV, when weighted by the 2–7 keV count rate, to 7.1 keV when the 14–50 keV count rate is used. Here we have employed the temperatures determined from the 2–12 keV fits. Even so, the exact value of the temperature is less important than the fact that the highly multi-temperature composite spectrum no longer looks like a single temperature plasma. The proper procedure is to use a truly multi-temperature model based on the temperatures of the constituent clusters, as we have done. We suspect that, if the thermal component is similarly modeled for the stacked spectrum of Nevalainen et al. (2004), the non-thermal excess will be reduced; however, it is unlikely that all of their excess would disappear.

Our most suggestive result from the various stacked subsamples, that clusters hosting a radio halo or relic have the the most significant indication of a non-thermal excess on average, is also the least surprising of possible outcomes. Because radio halos and relics are associated with mergers, which also produce shocks and multi-temperature gas distributions, the more appropriate thermal model to use might be the 2T<sub>j</sub> model. While the T+IC models have better  $\chi^2$  values, the differences are not significant enough to suggest that a non-thermal component is *required* to explain the spectrum. However, we can take the best-fit normalization, which agrees with the 2T<sub>j</sub> 90% upper limit, as an IC flux that can be

compared with the summed diffuse radio flux of the halos and relics to derive a lower limit on the average value of  $B$  for the Radio clusters. Following the IC/synchrotron theory outlined in Wik et al. (2009) using a total IC flux density at 1 keV of  $5.3 \mu\text{Jy}$  and a total radio flux density of  $1.385 \text{ Jy}$  at 1.4 GHz (excluding relics well-outside our extraction regions, such as those in A3667 and A1367), we find  $B > 0.13 \mu\text{G}$  for the lower limit on the average magnetic field in these clusters.

It may not be surprising that IC emission was not detected definitively in these clusters; direct measurements of cluster magnetic fields through Faraday rotation measure (RM) studies typically find line-of-sight  $B$  fields on the order of several  $\mu\text{G}$  (Govoni & Feretti 2004). Similar high values of  $B$  are suggested by the stability of cold fronts in merging clusters (Keshet et al. 2010), although the flow may amplify the fields in these regions. Also, RM magnetic field strengths could be biased high if stronger fields are correlated with denser gas, since RM observations are really measuring the electron density-weighted value of  $B$  along the line of sight (Petrosian 2001). Such explanations, while entirely reasonable, were primarily developed to explain the lower values of  $B$  implied by earlier IC detections, some of which have been more recently called into question (e.g., with *Suzaku*, Nakazawa et al. 2007, 2009; Wik et al. 2009). Our current sensitivity to IC emission with either pointed or survey observations can only detect non-thermal emission in clusters with radio halos if the magnetic fields are  $\lesssim 0.2 \mu\text{G}$ . Note that it is possible to observe much fainter IC emission at lower X-ray energies, and thus measure larger  $B$  fields, in radio relics that are significantly displaced from the bright gas in cluster centers (Finoguenov et al. 2010).

Can the survey observations with the BAT be improved, beyond the increase in sensitivity which comes with longer accumulating exposures? Perhaps the clearest way forward is to better calibrate the spectral response of the BAT in narrower channel so that the fluxes are more reliable for steep thermal emission in the 14–24 keV energy range. At present, we may be underestimating source fluxes in these bands. If the first band is low by  $\sim 2\sigma$  and the second by  $\sim 1\sigma$ , as suggested by the residuals in Figure 11, our non-thermal limits will increase by about  $1\sigma$  – a small but non-negligible amount. The most straightforward fix is to remake the survey using the BAT’s native 80 channels instead of binning them into 8 channels that are broad enough to be biased by the flux calibration with the Crab. With such improved data, this study can be repeated with a sample of all the known radio halo and relic clusters to definitively detect the non-thermal excess hinted at in the stacked “Radio” subsample considered here, if it exists.

Ultimately, any IC detections, especially if marginal, will have to be confirmed by the

upcoming missions with focussing hard X-ray telescopes, namely *NuSTAR*<sup>2</sup> and *Astro-H*<sup>3</sup>. By resolving both contaminating point sources and the location of the hottest gas, these missions have the potential to achieve higher sensitivities than have thus far been possible.

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